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HENRY S. GRAVES, Forester.

FOREST PRODUCTS LABORATORY SERIES.

PRINCIPLES OF DRYING LUMBER AT
ATMOSPHERIC PRESSURE
AND
HUMIDITY DIAGRAM.

BY

HARRY D. TIEMANN,

In Charge Timber Physics.



WASHINGTON:
GOVERNMENT PRINTING OFFICE,
1912.

FOREST SERVICE.

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LETTER OF TRANSMITTAL.

U. S. DEPARTMENT OF AGRICULTURE,
FOREST SERVICE,

Washington, D. C., January 26, 1912.

SIR: I have the honor to transmit herewith a manuscript entitled "Principles of Drying Lumber at Atmospheric Pressure," by Harry D. Tiemann, in charge timber physics, accompanied by a humidity diagram and discussion of its theory and use, and to recommend its publication as Bulletin 104 of the Forest Service.

Very respectfully,

HENRY S. GRAVES, *Forester.*

HON. JAMES WILSON,
Secretary of Agriculture.

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PRINCIPLES OF DRYING LUMBER AT ATMOSPHERIC PRESSURE.

PURPOSE OF EXPERIMENTS.

Methods of drying lumber have been the subject of so little systematic experimentation that scarcely any scientific information of value in commercial practice exists. What success is being obtained with dry kilns is the result of methods developed empirically. Most of the advantages claimed for the numerous methods of drying or types of kilns consist in superficial details, while the fundamental principles are passed over. The Forest Service has for a number of years made experiments in drying lumber on a small scale, and has reached what are believed to be fundamental principles. To learn how these principles may best be applied in commercial practice, two series of experiments are now under way; but in view of the interest in the subject, and the number of inquiries which are received, it is deemed desirable to publish immediately the conclusions already reached, as a guide to those who have to do with the problem of drying lumber.¹ To apply them effectively will require expert knowledge until the proper constants of operation have been determined, because no detailed method of operation can be prescribed at the present time. It is believed, however, that great improvement in methods of drying can be secured by applying these conclusions.

PART I. THE DRYING PROCESS AND ITS BASIC PRINCIPLES.

ESSENTIALS IN OPERATION.

Success in kiln drying depends on proper control of the two conditions of (1) heat and (2) relative humidity. Each step in the process should be considered with reference to what is essential in these two respects.

¹ The principles here discussed are those involved in the ordinary method of continuous drying, applicable to a commercial dry kiln operating at atmospheric pressure. For particular uses, other methods of drying or conditioning wood which involve principles not mentioned here may be desirable. Among these are methods requiring pressures greater and less than atmospheric, and high temperature treatment in gases other than air. One such method requiring alternate heating and cooling is described in a patent (No. 942150) granted the author Dec. 7, 1909. Methods for regulating the humidity are covered by U. S. patents No. 981818 of Jan. 17, 1911, and No. 963832 of July 12, 1910. The patents named are dedicated to the public.

The experiments made by the Forest Service indicate that successful dry-kiln operation requires the observance of the following points, which embody the basic principles of the process:

(1) The timber should be heated through before drying begins.

(2) The air should be very humid at the beginning of the drying process, and be made drier only gradually.

(3) The temperature of the lumber must be maintained uniformly throughout the entire pile. For this an exceedingly large circulation of air is essential.

(4) Control of the drying process at any given temperature must be secured by controlling the relative humidity, not by decreasing the circulation.

(5) In general, high temperatures permit more rapid drying than do lower ones. The higher the temperature of the lumber the more efficient is the kiln. It is believed that temperatures as high as the boiling point are not injurious to most woods, providing all the other fundamentally important factors are taken care of. Some species, however, may not be able to stand as high temperatures as others.

(6) The degree of dryness attained, where strength is the prime requisite, should not exceed that at which the wood is to be used.

DISCUSSION OF PROCEDURE.

PRELIMINARY TREATMENT.

The advantage of having the timber heated thoroughly before it goes into the kiln is that heat renders the wood more susceptible to the transmission of moisture. Since the water is evaporated from the surface only and must pass from the interior of the wood to the surface in order to be evaporated, the desirability of having the wood thoroughly warmed when the dry-kiln treatment begins is obvious. Where the wood can stand the heat without detrimental effects for the intended use, preliminary steaming not in condensed but in live steam is beneficial. This not only accomplishes the desired heating, but it assists in the transmission of moisture from the center also by moistening the surface if it is too dry. On the other hand, steaming greatly softens the tissue of the wood so that it becomes more or less plastic, as is well known in the wood-bending industry. Other effects, also, are produced which to a greater or less extent change the properties of the wood. The organic materials or "sap" in the wood are changed by "cooking," and apparently some undetermined chemical change takes place in the ligno cellulose of the wood itself. This is indicated by the fact that the color of the wood is darkened, the degree of coloring depending upon the temperature and duration of the process; and that the wood when subsequently dried has lost some

of its original weight and is less hygroscopic. The change in hygroscopicity is beneficial for some purposes, as it reduces swelling and shrinkage of the wood, but the wood is less resilient and if resoaked it becomes softer than the unsteamed material and in extreme cases even "punky." Very rich color effects are produced in hardwoods by sufficient steaming.

The pressure and duration of steaming desirable in kiln drying are points which have not yet been thoroughly worked out. From 5 minutes to 24 hours or even longer and pressures ranging from atmospheric to 50 pounds gauge have been used in practice. The higher the pressure the greater is the effect produced, and the longer the time the more thoroughly the treatment penetrates the wood. Experiments have shown that a pressure slightly above atmospheric for 24 hours is sufficient to slightly darken 2-inch maple clear through, and a pressure of 40 pounds will turn oak and probably other hardwoods almost black. Even where the strength of the wood is not the primary consideration, it probably is not safe to exceed 15 pounds gauge pressure (250° F.) except for special purposes.

REGULATING THE HUMIDITY.

The rate of evaporation may best be controlled by controlling the amount of vapor present in the air (relative humidity); it should not be controlled by reducing the air circulation, since a large circulation is needed at all times to supply the necessary heat.

The humidity should be graded from 100 per cent at the charging end to whatever humidity corresponds with the desired degree of dryness at the discharging end. The kiln should be so designed that the proper degree can be maintained at its every section. This may be accomplished either by suitable ventilation or by condensers at the sides.

Any well-made kiln which will fulfill the conditions required as to circulation and humidity control should work satisfactorily; but each case must be studied by itself and the various factors modified to suit the particular conditions of the problem. In every new case the lumber should be constantly watched and, if checking begins, the humidity should be increased until it stops. It is not reducing the circulation, but adding the necessary moisture to the air, that should be depended on to prevent checking. For this purpose it is well to have steam jets in the kiln.

The method which will be tried in the experiments previously referred to is distinctly original and consists briefly in water-spray condensers or humidity regulators placed in narrow chambers on the sides of the kiln. Simply by regulating the temperature of the water the relative humidity is controlled. The spray also accomplishes

the other fundamental requisite—maintaining a large circulation of air. Moreover, this system renders the kiln independent of outside atmospheric conditions. It is applicable either to the progressive or to the single compartment type of dry kiln.¹

REGULATING THE TEMPERATURE.

Heat serves two purposes: (1) It supplies the latent heat necessary for evaporating the water on the surface of the wood; (2) it renders the wood more permeable to the transmission of moisture from the center to the surface. Enough heat must be supplied for both purposes, and must come from the circulating air and vapor. The immense amount of air circulation required for evaporation will be realized when it is considered that each pound of free water evaporated, say at 150° F., requires slightly over 1,000 British thermal units of heat, or approximately the heat given out by 65,000 feet of dry air at 150° F. in falling 1° in temperature. It is therefore evident that a very large volume of air² is essential in order to keep a uniform temperature clear through to the center of each individual piece of wood, as well as to keep the temperature uniform throughout the pile, and at the same time to supply the additional heat required to produce evaporation. The heat, not the air, produces the evaporation; in fact, the pressure of the air retards evaporation, but the air and vapor are the means by which the heat is conveyed to the lumber. If, therefore, a large circulation of air is not secured, the supply of heat will be insufficient for both purposes, and the wood will surface dry, causing casehardening, honeycombing, and checking.

The circulation is best secured by the spontaneous currents within the kiln itself. These currents may be created by the air rising up through the steam coils, passing through the pile of lumber, and down again at the side walls, or in some other equally systematic and effective manner. To accelerate it the side walls should be kept cooler than the temperature of the rising air. In a progressive type of kiln the circulation should be entirely transverse.

USE OF SUPERHEATED STEAM.

In saturated air at atmospheric pressure no vaporization takes place until the boiling point is reached. Beyond this point the rate of vaporization depends solely upon the quantity of heat supplied. The free water in green wood may be driven off rapidly by heating the wood to the boiling point (which would be slightly above the

¹ The author has been granted two patents covering this water-spray humidity control and air-circulating method, which are dedicated to public use. The dates and numbers of the patents are 1019743, Mar. 5, 1912; and 1019999, Mar. 12, 1912.

² The heating capacity of vapor is about the same as that of air per given volume (see footnote, p. 9).

corresponding temperature for a vessel of water exposed to the same air pressure) and supplying the heat necessary for vaporization. This will not injure the wood, provided it is done in nearly saturated vapor; hence the applicability of superheated steam in drying lumber. The amount of heat available for evaporation will depend, in this case, on the quantity of steam and the number of degrees it is superheated, since the only means of heating the wood in a pile of lumber is by contact with the air or vapor passing through the pile.

But in drying lumber at atmospheric pressure the use of superheated steam involves certain difficulties, namely, the high temperature at which the drying must be conducted and the fact that the relative humidity of steam at atmospheric pressure decreases rapidly with increase of temperature. If the degree of superheat is great the relative humidity must be low and there will be danger of surface drying. If, on the other hand, the degree of superheating is slight, so as to retain a high relative humidity, then the amount of heat given to the wood is insufficient without an enormous circulation.¹ This difficulty does not exist in the case of air and vapor below the boiling point, since they permit the control of the relative humidity at any temperature. Therefore, superheated steam, though permitting rapid drying, requires a high degree of accuracy in the control of the kiln.

MAXIMUM RATE OF DRYING.

It follows from what has been said that successful kiln drying depends upon the proper control of heat and humidity. The right relation between these is that which will result in an equilibrium between the rate at which moisture is evaporated from the surface of the wood and the rate at which it is transmitted from the interior to the surface. When this relation is maintained the lumber dries without surface drying and consequent injury at the maximum rate possible for the given temperature. This rate is fixed by the physical process of transmission of moisture within the block of wood, and varies for different kinds of lumber.

The temperature of drying apparently influences the rate of transmission of moisture within the wood. The higher the temperature of the wood, the more rapid is the rate of transmission of the moisture, and hence the rate at which the moisture may safely be evaporated. This, of course, applies only to temperatures below the point where injury to the wood by heat might result. Moreover, the consideration here is entirely aside from questions of economy. Whether high

¹ This is evident when one considers that after the wood has once been raised to the temperature of the saturated steam the only additional heat which can be imparted must be due to the number of degrees the steam is superheated. The heating capacity of water vapor, per given volume, is but little greater than that of air; for, although the specific heat of water vapor at constant pressure is nearly double that of air—the former being 0.475 and the latter 0.237—its density at 100° C. is but 0.64 that of air.

temperatures are or are not the most economical this study does not attempt to determine. This will be discussed in a future bulletin now in preparation.

Neither casehardening nor checking can occur, except at temperatures well above the boiling point, until the surface of the wood has lost all its free water (i. e., water in liquid form filling the pores) and has reached its "fiber saturation point,"¹ for no shrinkage occurs until this point is passed.² The fiber saturation point, which lies between moisture conditions of 20 and 30 per cent of the dry weight of wood, is therefore a critical point in the drying.

DEGREE OF DRYING.

The degree to which wood should be dried is of importance. Drying renders wood more or less brittle, depending upon the degree to which the drying has been carried. Although the strength of wood increases with its degree of dryness, yet wood which has been dried and resoaked is less resilient than when green. Therefore, where strength is the prime consideration, it is important not to dry the wood beyond the degree at which it is to be used. On the other hand, where a reduction of the hygroscopicity and consequent "working," rather than strength, is the prime consideration, the wood should be thoroughly dried. For exacting service, where "working" must be reduced to a minimum, the wood, after thorough drying, should be stacked in the air several weeks or months until it reabsorbs the normal amount of moisture which it will contain in use. To insure any of these conditions the final stage of drying in the kiln should be conducted at a definitely prescribed humidity, since the amount of moisture remaining in the wood is directly proportional to the relative humidity in the surrounding air.

¹ See Forest Service Circular 108, Strength of Wood as Influenced by Moisture, pp. 7-11.

² Shrinkage in some woods, as oak, appears to take place at high temperatures, above 212° F., independent of this point, and in certain kinds of eucalyptus it begins with the first loss of moisture.

PART II. HUMIDITY DIAGRAM.

PURPOSE AND CONSTRUCTION.¹

The purpose of the humidity diagram is to enable the dry-kiln operator to determine quickly the humidity conditions and vapor pressures, as well as the changes which take place with changes of temperature. The diagram (fig. 1) is adapted to the direct solution of problems of this character without recourse to tables or mathematical calculations.

The humidity diagram consists of two distinct sets of curves on the same sheet. One set, the convex curves, is for the determination of relative humidity of wet-and-dry-bulb hygrometer or psychrometer;² the other, the concave curves, are derived from the vapor pressures and show the amount of moisture per cubic foot at different relative humidities and temperatures when read at the dew point. The latter curves, therefore, are independent of all variables affecting the wet-bulb readings. The short dashes show the correction (increase or decrease) which is necessary in the relative humidity, read from the convex curves, with an increase or decrease from the normal barometric pressure of 30 inches, for which the curves have been plotted. This correction, except for very low temperatures, is so small that it may usually be disregarded.

The ordinates, or vertical distances, are relative humidity expressed in per cent of saturation, from 0 per cent at the bottom to 100 per cent at the top. The abscissas, or horizontal distances, are temperature in degrees Fahrenheit from 30° below zero at the left to 220° above at the right.

EXAMPLES OF USE.

The application of the humidity diagram can best be understood by sample problems. These problems also show the wide range of conditions to which the diagram will apply.

(1) *To find the relative humidity by use of wet-and-dry-bulb hygrometer or psychrometer.*

Place the instrument in a strong circulation of air, or wave it to and fro. Read the temperature of the dry bulb and of the wet, and subtract. Find on the horizontal line the temperature shown by the dry-bulb thermometer. Follow the vertical line from this point till it intersects with the convex curve marked with the difference be-

¹ For the theory of the humidity diagram, see p. 14 and following of this circular.

² For a full explanation of the psychrometer, see Weather Bureau Bulletin No. 235, "Psychrometer Tables," and also "Smithsonian Meteorological Tables."

tween the wet and dry readings. The horizontal line passing through this intersection will give the relative humidity.

Example: Dry bulb 70° , wet 62° , difference 8° . Find 70° on the horizontal line of temperature. Follow up the vertical line from 70° till it intersects with the convex curve marked 8° . The horizontal line passing through this intersection shows the relative humidity to be 64 per cent.

(2) *To find how much water per cubic foot is contained in the air.*

Find the relative humidity as in example No. 1. Then the nearest concave curve gives the weight of water in grains per cubic foot when the air is cooled to the dew point. Using the same quantities as in example No. 1, this will be slightly more than 5 grains.

(3) *To find the amount of water required to saturate air at a given temperature.*

Find on the top line (100 per cent humidity) the given temperature; the concave curve intersecting at or near this point gives the number of grains per cubic foot. (Interpolate, if great accuracy is desired.)

(4) *To find the dew point.*

Obtain the relative humidity as in example No. 1. Then follow up parallel to the nearest concave curve until the top horizontal line (indicating 100 per cent relative humidity) is reached. The temperature on this horizontal line at the point reached will be the dew point.

Example: Dry bulb 70° , wet bulb 62° . On the vertical line for 70° find the intersection with the hygrometer (convex) curve for 8° . This will be found at nearly 64 per cent relative humidity. Then follow up parallel with the vapor pressure (concave) curve marked 5 grains to its intersection at the top of the chart with the 100 per cent humidity line. This gives the dew point as 57° .

(5) *To find the change in the relative humidity produced by a change in temperature.*

Example: The air at 70° F. is found to contain 64 per cent humidity; what will be its relative humidity if heated to 150° F.? Starting from the intersection of the designated humidity and temperature coordinates, follow the vapor pressure curve (concave) until it intersects the 150° temperature ordinate. The horizontal line then reads 6 per cent relative humidity. The same operation applies to reductions in temperature. In the above example what is the humidity at 60° ? Following parallel to the same curve in the opposite direction until it intersects the 60° ordinate gives 90 per cent; at 57° it becomes 100 per cent, reaching the dew point.

(6) *To find the amount of condensation produced by lowering the temperature.*

Example: At 150° the wet bulb reads 132° . How much water would be condensed if the temperature were lowered to 70° ? The intersection of the hygrometer curve for 18° ($150^{\circ}-132^{\circ}$) with temperature line for 150° shows a relative humidity of 60 per cent. The vapor-pressure curve (concave), followed up to the 100 per cent relative humidity line, shows 45 grains per cubic foot at the dew point, which corresponds to a temperature of 130° . At 70° it is seen that the air can contain but 8 grains per cubic foot (saturation). Consequently there will be condensed 45 minus 8 or 37 grains per cubic foot of space measured at the dew point.

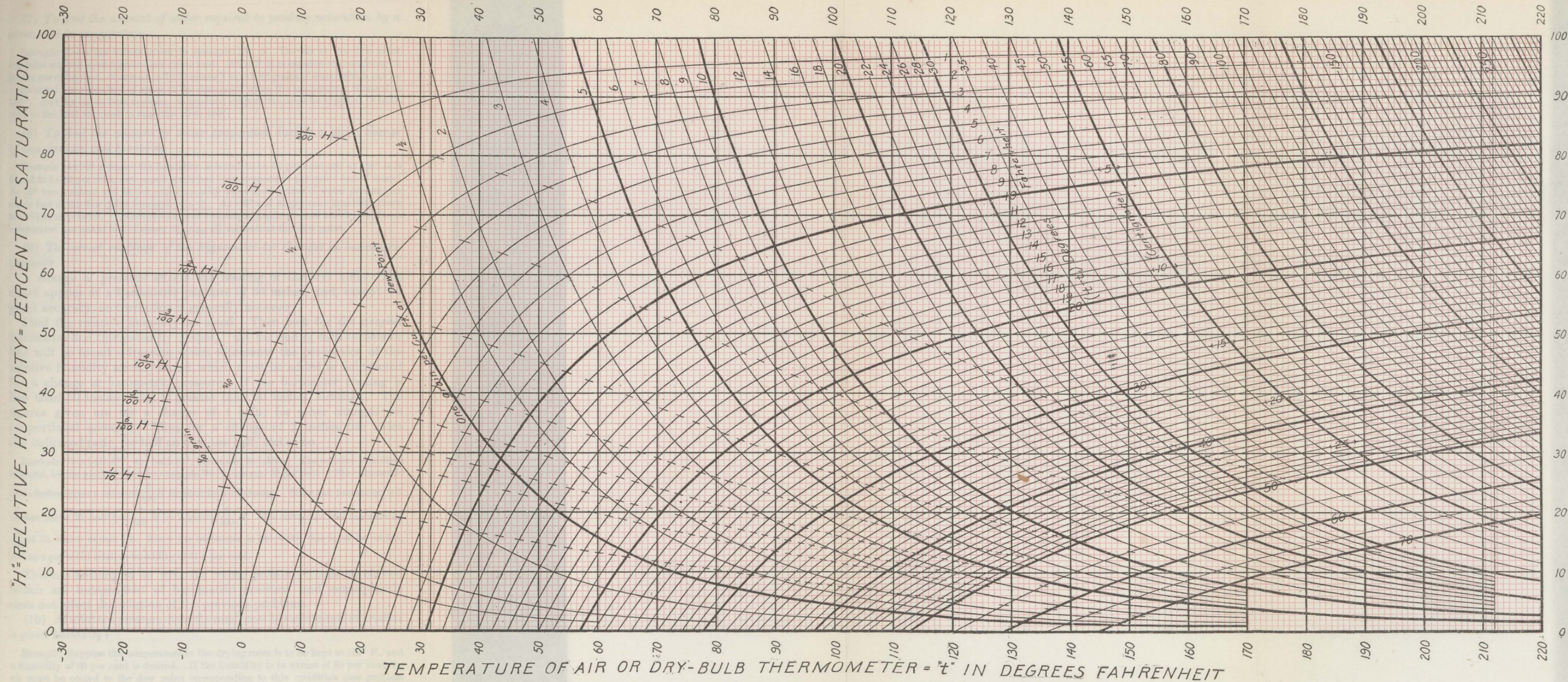


FIG. 1.—Humidity diagram. For determination of absolute humidities, dew points, and vapor pressures; also relative humidities by means of wet-and-dry-bulb thermometer, for any temperature and change in temperature.

(7) *To find the amount of water required to produce saturation by a given rise in temperature.*

Example: Take the values given in example No. 5. The air at the dew point contains slightly over 5 grains per cubic foot. At 150° it is capable of containing 73 grains per cubic foot. Consequently 73 minus 5 equals 68 grains of water which can be evaporated per cubic foot of space at the dew point when the temperature is raised to 150° . But the latent heat necessary to produce evaporation must be supplied in addition to the heat required to raise the air to 150° .

(8) *To find the amount of water evaporated during a given change of temperature and humidity.*

Example: At 70° suppose the humidity is found to be 64 per cent and at 150° it is found to be 60 per cent, how much water has been evaporated per cubic foot of space? At 70° temperature and 64 per cent humidity there are 5 grains of water present per cubic foot at the dew point (example No. 2). At 150° and 60 per cent humidity there are 45 grains present. Therefore 45 minus 5 equals 40 grains of water which have been evaporated per cubic foot of space, figuring all volumes at the dew point.

(9) *To correct readings of the hygrometer for changes in barometric pressure.*

A change of pressure affects the reading of the wet bulb. The chart applies at a barometric pressure of 30 inches, and, except for great accuracy, no correction is generally necessary.

Find the relative humidity as usual. Then look for the nearest barometer line (indicated by dashes). At the end of each barometer line will be found a fraction which represents the proportion of the relative humidity already found, which must be added or subtracted for a change in barometric pressure. If the barometer reading is less than 30 inches, add; if greater than 30 inches, subtract. The figures given are for a change of 1 inch; for other changes use proportional amounts. Thus for a change of 2 inches use twice the indicated ratio, for half an inch use half, and so on.

Example: Dry bulb 67° , wet bulb 51° , barometer 28 inches. The relative humidity is found, by the method given in example No. 1, to equal 30 per cent. The barometric line (dashes) gives a value of $\frac{3}{100}H$ for each inch of change. Since the barometer is 2 inches below 30, multiply $\frac{3}{100}H$ by 2, giving $\frac{6}{100}H$. The correction will therefore be $\frac{6}{100}$ of 30, which equals 1.8. Since the barometer is below 30, this is to be added, giving a corrected relative humidity of 31.8 per cent.

This has nothing to do with the vapor pressure (concave) curves, which are independent of barometric pressure, and consequently does not affect the solution of the previous problems.

(10) *At what temperature must the condenser be maintained to produce a given humidity?*

Example: Suppose the temperature in the drying room is to be kept at 150° F., and a humidity of 80 per cent is desired. If the humidity is in excess of 80 per cent the air must be cooled to the dew point corresponding to this condition (see problem No. 4), which in this case is 141.5° .

Hence if the condenser cools the air to this dew point, the required condition is obtained when the air is again heated to the initial temperature.

(11) *Determination of relative humidity by the dew point.*

The quantity of moisture present and relative humidity for any given temperature may be determined directly and accurately by finding the dew point and applying the concave (vapor pressure) curves. This does away with the necessity for the empirical convex curves and wet and dry bulb readings. To find the dew point some form of apparatus, consisting essentially of a thin glass vessel containing a thermometer and a volatile liquid, such as ether, may be used. The vessel is gradually cooled, through the evaporation of the liquid, accelerated by forcing air through a tube, until a haze or dimness, due to condensation from the surrounding air, first appears upon the bright outer surface of the glass. The temperature at which the haze first appears is the dew point. Several trials should be made for this temperature determination, using the average temperature at which the haze appears and disappears.

To determine the relative humidity of the surrounding air by means of the dew point thus determined, find the concave curve intersecting the top horizontal (100 per cent relative humidity) line nearest the dew-point temperature. Follow parallel with this curve till it intersects the vertical line representing the temperature of the surrounding air. The horizontal line passing through this intersection will give the relative humidity.

Example: Temperature of surrounding air is 80°; dew point is 61°; relative humidity is 53 per cent.

The dew-point determination is, however, not as convenient to make as the wet-and-dry-bulb hygrometer readings. Therefore, the hygrometer (convex) curves are ordinarily more useful in determining relative humidities.

THEORY OF HUMIDITY DIAGRAM.

RELATIVE HUMIDITY CURVES.

The relative humidity or convex curves are empirical, depending upon experimental data furnished by the United States Weather Bureau. The curves are based on Ferrel's formula:¹

$$f = f_1 - 0.000367 P (t - t_1) \left(1 + \frac{t_1 - 32}{1571} \right)$$

in which

t = temperature of the dry bulb in degrees Fahrenheit.

t_1 = temperature of the wet bulb in degrees Fahrenheit.

¹ For this formula and for much of the tabulated data upon which the curves are based, the author is indebted to the publications of the Weather Bureau and Smithsonian Institution referred to in the second footnote on p. 11.

f = actual vapor pressure in the air in inches of mercury.

f_1 = maximum vapor pressure at the temperature of wet bulb t_1 .

P = barometric pressure in inches of mercury.

If F be the maximum vapor pressure at the dry-bulb temperature t , then the relative humidity is $\frac{f}{F}$.

The constants for Ferrel's equation were obtained by a great number of careful experiments conducted by Profs. Marvin and Hazen, of the United States Weather Bureau. The equation applies correctly only when the psychrometer is subjected to a strong current of air having a velocity of at least 15 feet per second. It is strictly applicable only below 140° F., since the constants of the equation have been deduced from experiments conducted only at temperatures below this. Experiments made by the author indicate, however, that the equation holds with reasonable exactness for temperature up to the boiling point, and the curves have therefore been extended to 220° .

The curves as plotted are for a barometric pressure of 30 inches, and since P enters into the equation a correction must be made for exactness at other pressures. This correction is shown by the intersecting dashes as a proportion of the indicated humidity, so that it may be made direct from the curves with little extra calculation. These correction lines were derived in the following manner:

Let P and H be the variables and t , t_1 , f_1 , and F constant. Let C be a constant factor.

$$\frac{H = f_1 - CP}{F} \qquad \frac{H_1 = f_1 - CP_1}{F} \qquad (1)$$

Then,

$$\frac{H_1 - H}{H} = \left(\frac{f_1 - CP_1}{F} - \frac{f_1 - CP}{F} \right) \times \frac{F}{f_1 - CP} = \frac{C(P - P_1)}{f_1 - CP} \qquad (2)$$

That is, other things being constant the ratio $\frac{H_1 - H}{H}$ is directly proportional to the difference in pressures $(P - P_1)$. Let $P - P_1 = 1$, then

$$\frac{H_1 - H}{H} = \frac{C}{f_1 - CP}$$

Now assume a value for $\frac{H_1 - H}{H}$, say $\frac{1}{100}$, then

$$\frac{C}{f_1 - CP} = \frac{1}{100}, f_1 = 100 C + CP.$$

But P was taken as 30 in the given curves, therefore

$$f_1 = \frac{130}{30} CP, = \frac{13}{3} CP \qquad (3)$$

So also for $\frac{H_1 - H}{H} = \frac{2}{100}$, $f_1 = \frac{16}{6} CP$, etc.

Now, with these values for f_1 corresponding to $\frac{1}{100}$, $\frac{2}{100}$, etc., proportional differences in the values of H for a 30-inch barometer reading, the values of CP may be calculated for various differences $(t-t_1)$ and the values of f_1 found from this equation (3). The temperature t_1 is thus determined corresponding to f_1 and therefore also the temperature t .

Hence, points may be marked on the curves corresponding to a difference in barometric pressure of 1 inch and a proportional value of H added to or subtracted from the value derived straight from the curves. This proportion is given at the left-hand end of these barometric lines. It will be seen from equation (2) that this amount must be added to H for barometer readings less than 30 inches, and subtracted for readings above 30 inches. The amount is also seen to be directly proportional to the difference in pressure, so that for a fall of barometer of 2 inches twice the indicated amount must be added.

Except for very low temperatures this correction is so small that it may usually be disregarded.

VAPOR-PRESSURE CURVES.¹

The vapor pressure or concave curves indicate the relative humidity or proportional saturation of the air which definite amounts of moisture, read at the dew point, will produce at given temperatures. The amounts of moisture are given on the curves in grains per cubic foot of air (or space) at the dew point or saturation. The exact weight of moisture present is not given, except at the dew point as just stated.

The curves might have been drawn to show the exact weight of moisture present at any given temperature and relative humidity, but by so doing their chief function, the ability to indicate the concurrent variation of the moisture condition with change of temperature, would have been lost. If the barometric pressure remains constant while the temperature changes, the vapor pressure also remains constant; but not so the weight of moisture per cubic foot. The relative humidity is the ratio of the actual vapor pressure to the maximum vapor pressure; hence by drawing these curves to represent vapor pressures instead of weights of vapor, they may be followed strictly from one temperature to another for determining the change which will occur in the relative humidity. The difference between the density (weight) curves and the vapor-pressure curves is comparatively small, however, within the range of temperature given, and the curves may be read in terms of grains per cubic foot

¹ Not to be confused with saturate vapor-pressure curves.

at any point without great error. For example, take a cubic foot of saturated air at 70° F. and heat it to 100°. The concave curves of the humidity diagram show that it originally contained 8 grains of moisture; the saturated vapor-pressure curve shows that the saturate vapor pressure was 0.73 inch of mercury. In heating to 100°, the total pressure of air plus moisture remains unchanged, and therefore the vapor pressure is still 0.73 inch. The vapor, however, has been expanded by the heat so that it now occupies

$$\frac{t_0 + 100}{t_0 + 70} = \frac{561}{531} = 1.056 \text{ cubic feet,}$$

t_0 being the absolute temperature Fahrenheit. One cubic foot therefore contains $\frac{8}{1.056} = 7.57$ grains. The relative humidity by the curves is seen to be 38 per cent $\left(= \frac{0.73}{1.92} \right)$. Had this air been heated to 170°, 1 cubic foot would contain 6.73 grains instead of 8, and its relative humidity would be $\frac{0.73}{12.2} = 6$ per cent, which is shown on the curve. The denominators are pressures of saturated vapor (in inches of mercury) at the respective temperatures.

SATURATE VAPOR-PRESSURE CURVES.

The four curves shown in figure 2 represent pressures of saturated vapor, the vertical lines (ordinates) being pressures in inches of mercury, and the horizontal lines (abscissas) being temperatures. They are in reality one curve drawn in four parts, in as many different scales, each of which is the previous scale magnified by ten. For example, the units on the first part of the curve (on the extreme right) are inches; when the curvature decreases so that this scale can not be read accurately, the curve is broken, and the second part is drawn in units of 0.1 inch. Similarly the units shown on the third and fourth parts are, respectively, 0.01 and 0.001 inch.

MEASURES AND WEIGHTS.

The following equivalents are given for convenience in making computations:

9° F. = 5° C.

1 inch = 25.4 mm.

1 meter = 39.37 inches.

1 grain = 0.06480 grams.

1 gram = 15.4324 grains.

1 grain per cubic foot = 0.0022883 grams per liter.

1 gram per liter = 436.99 grains per cubic foot.

7,000 grains = 1 pound av. = 453.59 grams.

1 U. S. gallon water at 62° F. weighs 8.3360 lbs. av.

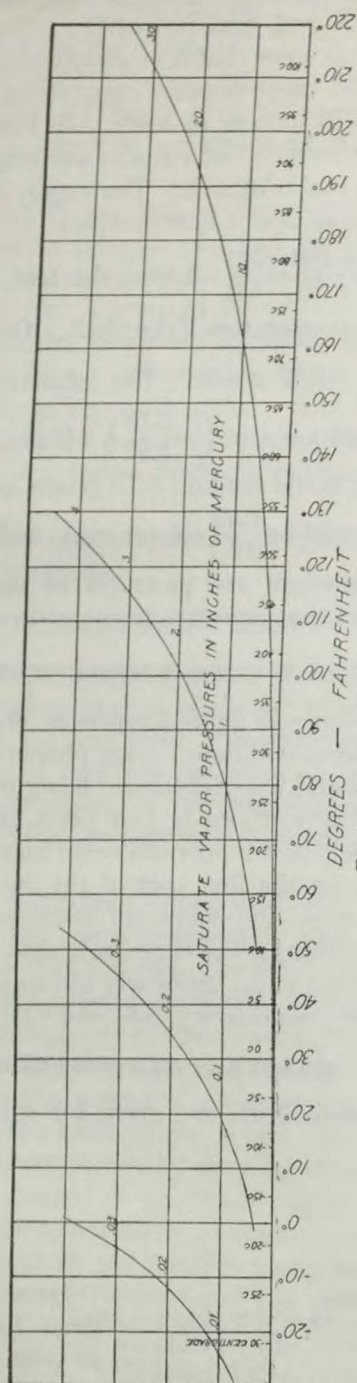


Fig. 2.—Saturate vapor-pressure curves.

- 1 cu. ft. water at 62° F. weighs 62.36 lbs. av.; at 39° F. (maximum density) 62.43.
- 1 U. S. cu. ft.=7.48 U. S. gallons.
- 1 U. S. gallon=231 cubic inches.
- 1 imperial gallon water at 62° F. weighs 10 lbs. av.=277.11 cubic inches.
- 1 cu. ft.=6.236 imperial gallons.
- 1 U. S. gallon=3.785 liters.
- 1 imperial gallon=4.541 liters.
- 1 cu. ft.=28.317 liters.

